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ORIGIN AND SIGNIFICANCE OF OPENWORK GRAVEL

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PAPERS

ORIGIN AND SIGNIFICANCE OF OPENWORK GRAVEL

By Allen S. Cary,[1] Assoc. M. ASCE

Synopsis

Openwork gravel, without interstitial sand, is found associated with stream deposits of well graded sand and gravel in innumerable exposures throughout the Pacific Northwest. A study of the relationships suggests that openwork gravel is deposited by swift streams on the downstream face of a gravel bar or as sloping beds on a delta face. Vortex action may be partly responsible for the absence of sand in the deposit. Openwork gravel is of significance in engineering works involving water because of its common occurrence, the usual lenticular shape of a deposit, and its extremely high permeability.

Introduction

Openwork gravel differs markedly from what might be called "normal" gravel in that it is composed entirely of pebbles having a narrow range of sizes. In the absence of interstitial sand the pebbles are in mutual contact, leaving large open voids which form continuous passages for long distances. Normal gravel as considered in this paper is a fairly well graded mixture of sand and gravel in which pebbles of a wide range of sizes are scattered throughout a sand matrix.

In conducting geologic studies for engineering works in the Northwest, the writer has seen hundreds of lenses of openwork gravel in natural and artificial cuts in gravel terrace remnants. Attention has been focused upon it with increasing intensity because it differs greatly from normal gravel in certain physical properties which are significant to the engineering geologist. The limited number of references to it in the literature suggests that it has been either overlooked or disregarded in geologic studies of gravel deposits.

The purpose of this paper is to discuss the mechanics of deposition of this special type of fluvial sediment and the significance of its origin to certain types of engineering problems.

Note.—Written comments are invited for publication; the last discussion should be submitted by **October 1, 1950.**

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Characteristics

Figs. 1 and 2 illustrate the distinctive characteristics of openwork gravel—that is, (*a*) the total absence of sand between the pebbles and (*b*) the limited range of pebble sizes. Most of the pebbles in openwork gravel fall within the size range of the larger pebbles in the normal gravel with which they are

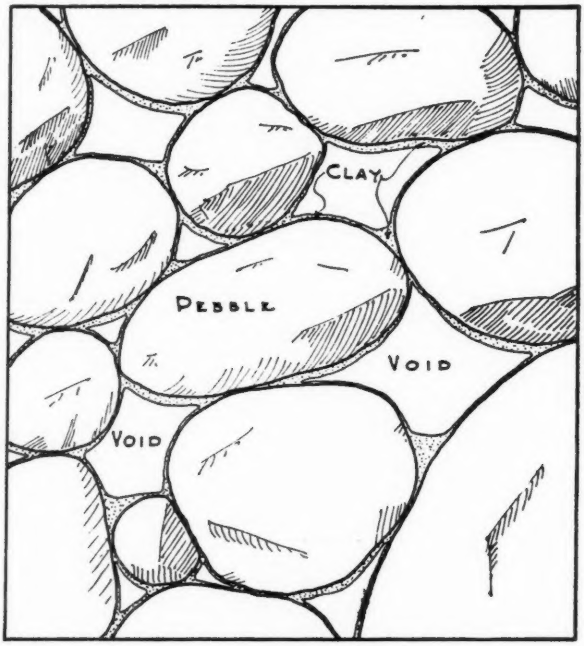

Fig. 1.—Openwork Gravel

associated. The contrast is seen clearly in Fig. 2, which includes seven mechanical gradation curves of openwork gravel samples from various occurrences in the Northwest, and in curve No. 8, which illustrates well graded normal gravel. Most of the pebbles within a lens of openwork gravel might range from $\frac{1}{16}$ in. to $\frac{1}{4}$ in. in diameter, or from 3 in. to 6 in. in diameter; whereas in the associated normal gravel the particles might range downward from a corresponding maximum through sand to 0.001-in. diameter. There is, in fact, every gradation in the structure, from all one size of particle (with completely open voids, as in Fig. 3) to a relatively wide range of particle sizes, in which the voids become smaller with the additional small size particles (Fig. 4), approaching what is here termed normal gravel.

Occurrence

Most of the deposits of openwork gravel observed by the writer, together with the associated normal gravel, are in glacial stream and delta deposits. This is explained by the simple fact that the glacial history of the Northwest

involves, during one or more stages, large-scale filling and trenching in the valleys and in the Puget Sound lowland in Washington. The terraces resulting from the filling and trenching are often directly or indirectly involved in engineering works. The presence of openwork gravel in river bars now in process of formation on the Columbia River in Washington, the Kootenai River in Montana, and the Skagway River in Alaska indicates that the structure is not peculiar to glacial outwash, or to aggradation as such, but may develop in any high-velocity stream carrying gravel bed load. Indeed, openwork pea gravel has been observed forming as sloping beds on a miniature delta face in a puddle after a rainstrom.

The most common occurrence of openwork gravel is in lenses associated with normal gravel and with sand. The openwork structure is best developed in lenses exhibiting torrential bedding, as illustrated in Fig. 5. The torrentially bedded openwork lenses usually range up to a maximum of 6 ft in thickness and a few tens of feet in length. The largest individual lens of this type so far observed is 120 ft long and evidently represents the filling of a scour channel in a stream bed by the downstream growth of a gravel bar. Although this and most other examples are parts of valley fills, it is certain that aggradation as

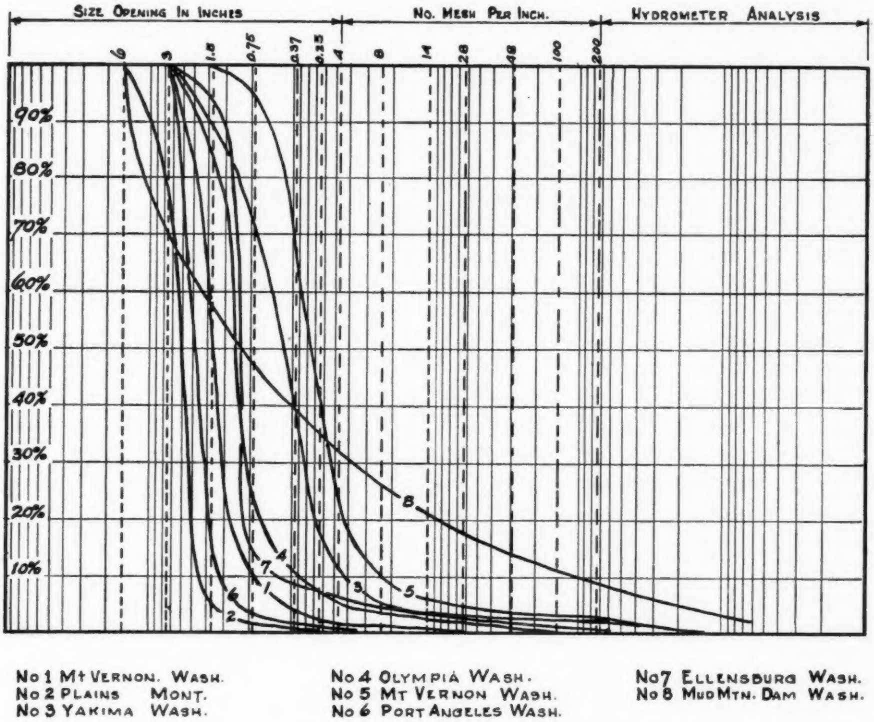

Fig. 2.—Mechanical Analysis

such is only incidental; precisely the same scouring and filling processes are in operation in graded and slowly degrading streams.

In a second type of occurrence, the openwork lenses lie as sloping beds deposited on the forward faces of gravelly deltas during their formation. The

FIG. 3.—GRAVEL WITH OPEN VOIDS

fact that they are surrounded by sloping beds consisting of normal gravel with the same maximum pebble sizes indicates that the contrast must be due to some slight variation in conditions of deposition. Certain deposits which appear to be delta bedding may in fact be torrential bedding, deposited in very large glacial outwash streams.

In small exposures the torrentially bedded occurrences cannot be distinguished from delta beds. Under certain conditions in glaciated areas, as should be expected, one will grade into the other. The torrentially bedded structure may also grade into a third type, in which the pebble bedding is essentially parallel to the horizontal stratification of the associated normal gravel. This third type is relatively rare and usually not more than a few pebbles thick. The general relationships are shown in Fig. 5.

EARLY OBSERVATIONS

Haakon Wadel[2] (1936–1937) and William Morris Davis[3] (1890–1892) have each mentioned openwork gravel in connection with a special type of glacial

[2] "Volume, Shape and Shape Position of Rock Fragments in Openwork Gravel," by Haakon Wadel, *Geografiska Annaler*, 1936–1937, p. 99.

[3] "The Subglacial Origin of Certain Eskers," by W. M. Davis, *Proceedings, Boston Soc. of Natural History*, 1890–1892, p. 499.

stream deposit, but neither suggests the mechanics of deposition in the usual swift-flowing stream. A. W. Grabau[4] (1913) mentions the fact of separation of pebbles from sand as a beach process, but makes no mention of stream-deposited openwork gravel. This paper deals almost exclusively with open-

FIG. 4.—WIDE RANGE OF PARTICLE SIZES WITH SMALL VOIDS

work gravels which may be deposited in any swift-flowing stream, so that these special occurrences will not be discussed further.

ORIGIN OF OPENWORK GRAVEL

The stratification of openwork gravel and its association with normal gravel indicate clearly that the most common occurrence is on the downstream face of a bar in a stream bed. Thus, the openwork gravel may be deposited as a result of the pebbles being rolled along the bar top by the stream current and coming to rest at their angle of repose underwater on the downstream face, whereas the finer material is carried on downstream. The ever-changing stream bed topography results in ever-changing current direction and velocity, so that sand or normal gravel is often found completely surrounding the openwork gravel in any exposure.

[4] "Principles of Stratigraphy," by A. W. Grabau, A. G. Seiler & Co., New York, N. Y., 1913, p. 701.

Gerard H. Matthes,[5] Hon. M. ASCE (1947), attributes much stream erosion of bedrock to large-scale turbulence on the lee side of projections into a stream. Careful observation from a canoe on the Kootenai River, on the Clark Fork of the Columbia River in Montana, and on the Columbia River in Washington

FIG. 5.—LENSES OF OPENWORK GRAVEL ASSOCIATED WITH NORMAL GRAVEL AND SAND

reveals analogous, although less vigorous, action at the downstream face of gravel bars in the stream beds. The simple case described in the preceding paragraph may not actually occur without the assistance of identical turbulence.

A vortex, forming at the downstream face of a bar, would lower the hydraulic pressure at the bar face, and would cause a movement of water outward from within the interstices of the gravel in the bar. Any sand that had been deposited on the bar face would tend to be removed and that sand which might have been deposited during the life of the vortex would be carried downstream. At the same time, the vortex might not be strong enough to prevent deposition of the pebbles that rolled over the bar face during that period. A nearly stable or continuous vortex, or a long series of vortices in succession, would keep the sand cleaned out of a bar face long enough for an indefinite length of openwork gravel to be deposited.

[5] "Macroturbulence in Natural Stream Flow," by Gerard H. Matthes, *Transactions*, Am. Geophysical Union, April, 1947, p. 255.

Significance is attached to the observation that the pebble sizes found in openwork gravel are usually in the size range of the larger pebbles in the normal gravel with which the openwork gravel is associated. It suggests a self-evident but definite relationship between the current velocity (as evidenced by the caliber of its load) and the lifting power of the vortices (as evidenced by the caliber of load that remains after selective removal of the finer fractions).

Openwork gravel is considered to result from the ordinary processes of selective transportation and deposition, brought on by local variations in water velocity and by turbulence in rapid streams, and is considered to be one phase of the total deposit of any swift, gravel-bearing stream.

Secondary Deposits Within Voids

The clay coating (see Fig. 1) around each pebble in many openwork gravel lenses marks an entirely different phase of deposition. Water in the interstices, at any appreciable depth below a stream bottom, has little movement; but there will be enough circulation to carry clay, of colloidal dimensions, into the sands and gravels.

Water moving through gravel below stream level finds its way, by tortuous paths, among the sand grains, with low velocity. Silt particles and some colloids are filtered out in the process; but the balance of the colloids continues to move until the colloids are precipitated as a result of flocculation and a reduction in the rate of movement of water. When the water finds its way to an openwork gravel lens, its velocity is immediately checked, because of the very great increase in size and volume of the voids and the reduction in resistance to flow.

The openwork gravel is many times more permeable than the normal gravel which surrounds it; but the rate of movement through the entire deposit is generally governed by the permeability of the normal gravel rather than that of the openwork gravel—as if there were a series of large reservoirs in a body of normal gravel, with the rate of flow through the reservoirs being governed by the rate at which water can enter and leave through the surrounding sand and gravel. The colloids then may be precipitated out in the reservoir of openwork gravel voids and may tend to be concentrated on the bottom side of the pebbles by the downward component of movement of water.

When aggradation ceases and stream downcutting begins, the gravel deposit becomes subject to drainage. In the years or centuries after drainage of a deposit, downward circulating water may be partly, or almost wholly, responsible for the presence of the clay on the bottom of pebbles in greater quantity than on the top or sides. The downward circulation of water may also explain why some of the interstitial clay is found as partial void filling on the "floor" of a void, which frequently exhibits horizontal laminations. Whether the variations in thickness of clay are original depositional features, or secondary characteristics imposed by downward circulating water after drainage of the deposit, has no direct bearing on the origin of the gravel itself.

A special case of complete void filling will be discussed in another connection under Chief Joseph (formerly Foster Creek) dam site on the Columbia River in the State of Washington.

Examples of Special Interest

(*a*) *Columbia River and Plateau.*—H. T. Harding[6] (1929) has indicated that the sudden lowering of glacial Lake Missoula played a dominant part in supplying the water to shape the erosional and depositional features of the channeled scablands of Washington described by J. Harlen Bretz[7] (1923). The writer has observed openwork gravel in bars from within the area once covered by glacial Lake Missoula, westward and southward throughout the channeled scablands, Moses Coulee, Grand Coulee, and the Washtucna, Priest Rapids, and Hanford areas in Washington. Many of these were observed in connection with geologic investigation for engineering structures.

(*b*) *Plains, Mont.*—J. J. Pardee[8] (1940) has described evidence of unusual currents in glacial Lake Missoula. About 2 miles downstream (west) from the town of Plains, on the Clark Fork of the Columbia River, an enormous gravel bar occurs, more than 300 ft thick and covering 5 sq miles, which is one additional current-built feature that bears further testimony as to the strength of the currents described by Mr. Pardee. The internal structure of the bar was revealed by trenching on the riverward slope and by drilling on the bar surface, under the supervision of the writer during exploration for a possible dam site. It consists wholly of openwork gravel and boulders, with some silt; but no clay coating or complete void filling was found. Evidently the entire bar accumulated in one extreme rush of water. The silt may have been entrapped within the gravel, or may have been carried downward from the surface by recent percolating water.

At the downstream end of this bar, the rock walls of the Clark Fork Valley close in and appear to present favorable conditions for an alternate dam site. Drilling in the valley bottom revealed more than 170 ft of openwork boulders and angular blocks of country rock ranging from 1 ft to 4 ft in diameter. The voids in the upper 50-ft stratum of boulders were filled or nearly filled with silt; but, at greater depth, the voids were absolutely open. Water level in the 6-in. drill casing could not be raised by pumping in at the rate of 75 gal per min. Indeed, it was also impossible to raise the water level, with the same pump, in a casing sunk by drilling on the Plains bar. Both dam sites were declared not feasible because of the extremely high permeability of the openwork materials.

(*c*) *Mount Vernon, Wash.*—Of special interest is a deposit near Mount Vernon, which has about 40% of the pebbles crushed and broken as a result of vertical loading. A deposit of Vashon (Wisconsin) glacial till overlying the gravel indicates that the area was covered by ice after the gravel was deposited. The occurrence of Vashon gravel and other ice marginal features high on adjacent mountain slopes indicates that no less than 4,000 ft of ice covered the area during the Vashon glacial stage. If the glacial ice is assumed to have had a specific gravity of 0.9, the pressure intensity under the ice would have been

[6] "Possible Water Supply for the Creation of Channeled Scab Lands," by H. T. Harding, *Science*, February 15, 1929, pp. 188–190.

[7] "The Channeled Scablands of the Columbia Plateau," by J. Harlen Bretz, *Journal of Geology*, November–December, 1923, p. 617.

[8] "Ripple Marks (?) in Glacial Lake Missoula, Montana," by J. T. Pardee, *Bulletin*, Geological Soc. of America, December, 1940, pp. 2028–2029 (abstracts).

about 224,000 lb per sq ft. In the openwork gravel this load was distributed over a comparatively few points of contact on any single square foot of area. The unit pressures exceeded the ultimate strength of the gravel particles, with the resulting breakdown of the points of contact. The normal gravel in the same exposure was subject to the same pressure; but, because of the greater distribution and lesser intensity of pressure on the innumerable points of contact between the sand and gravel particles, the crushing did not occur. Examination of the gravel reveals that each pebble in the Mount Vernon deposit is deeply weathered, whereas many other gravels lying similarly under Vashon till are fresh and unweathered. There seems little doubt, therefore, that this deposit was weathered at the time of invasion by the ice which deposited the till and explains the crushing of the individual pebbles. Fresh openwork gravel lying directly under till near the international border, where the ice was at least 1,000 ft thicker, shows no crushing.

Engineering Significance of Openwork Gravel

Filter Investigation.—During an experimental investigation of gravel filters, it was noted that water percolating downward through pit run gravel containing the clay mineral, montmorillonite (a bentonite type of clay), carried the clay into the clean filter material and deposited it on the underside of the individual pebbles in the filter. The mechanics of deposition of the clay within the filter appears to be identical to the deposition within openwork gravel in a natural deposit.

Earth Fill Materials.—The presence of clay in the voids of openwork gravel lenses affects the properties of an entire gravel deposit in such a manner that its value as a construction material may be rather limited. When a gravel pit is opened, vertical faces may stand for years with little raveling. A cut face of gravel, or of sand, exposed to the sun and protected from infiltrating water from above by an impervious till blanket, may appear very dry. A few inches inward from the cut face, however, the moisture content may be very high. When the material is excavated and thoroughly mixed for use as construction material, the mixture of clay, sand, and gravel may have the consistency of "cup grease and marbles." The explanation is simple: When the material is deposited by streams, there is good rock-to-rock contact, with an interlocking of rock particles. The clay, deposited later, is distributed everywhere as a coating around each pebble and sand particle, except at the mutual contacts. When the clay, sand, and gravel are thoroughly mixed, each pebble and sand grain becomes completely coated with wet clay and the entire mass may have a surprisingly low bearing capacity, especially if the water content of the clay is high. Since there is a very small percentage of the clay present, a slight change in moisture content has a very marked effect on the engineering properties of the material.

Water Jetting.—A jet pipe may penetrate vertically downward through sand or normal gravel without much difficulty, because the sand will usually wash up along the outside of the pipe. The removal of sand allows room for the pebbles to be displaced by the jet pipe. When a lens of openwork gravel is encountered, there is no sand to be washed out to make room for the jet pipe.

The pebbles, being in mutual contact and generally well interlocked, form an impassable barrier to jet pipes.

Permeability Characteristics.—The permeability characteristics of gravel deposits in their undisturbed condition are often among the most important questions confronting the engineer in the design and construction of dams, levees, drainage or irrigation canals, and other works involving water. Since openwork gravel usually occurs in lenses surrounded by normal gravel, one may easily be led to the erroneous conclusions that the permeability of a section of gravel is controlled by the normal gravel and that the openwork lenses constitute enlargements in the innumerable conduits that will act merely as reservoirs, and nothing more. Over very long distances this may be true; but the effective length of seepage path may be reduced an appreciable amount by the presence of strata that are particularly rich in openwork gravel lenses.

As stated, lenses have been measured which are 120 ft long and such lenses may be scattered through a deposit with only a foot or two of normal gravel (or of sand) between them. If the lenses are arranged in such a manner that their ends are separated by only a foot or two of sand and gravel it is conceivable that several hundred feet of gravel may prove to be 90% openwork gravel and only 10% normal gravel, in a horizontal path. Suppose that a dam is built abutting against a gravel bank so that water is ponded to a depth of 50 ft and the seepage path through the gravel is 500 ft. The hydraulic gradient would thus be 50/500, or 0.1. Suppose that in the 500 ft of gravel there are 450 ft of openwork gravel lenses and only 50 ft of effective normal gravel or sand. If this occurs near the bottom of the abutment, the effective gradient might be considerably higher than the measured gradient. Internal piping through sand lenses into openwork gravel might occur, thus creating an almost continuous path for water seepage with little frictional resistance.

Chief Joseph Dam Site.—The Chief Joseph dam site on the Columbia River, 51 miles downstream from the Grand Coulee Dam (Washington), is being studied by the Seattle District, Corps of Engineers, for development of 165 ft of available head for power. The foundation and left abutment are excellent granite for all the structures. The right abutment consists of 110 ft of gravel resting on the nearly level bedrock floor. The gravel is overlain by about 180 ft of extremely hard, impervious glacial till, forming a terrace into which the river has cut a 300-ft canyon to bedrock.

The very unusual nature of the gravel presents a major seepage problem both during construction, when the right abutment will be dewatered, and, after construction, for the control of seepage water in the zone of emergence

Test pits, drill holes, tunnels, and stopes have revealed that about 50% of the bulk of the stratum is openwork gravel. Indirect evidence strongly suggests that the permeability of this stratum is completely controlled by the openwork gravel and that the associated normal gravel occurs in isolated lenticular bodies that have no effect on the permeability except as they may reduce the effective cross-sectional area of the openwork stratum.

The evidence upon which this statement is based is the fact that the water surface in test pit 2A, which is about 1,100 ft from the river, lagged but 2 ft

below the river during the rise of April-May, 1948. This constituted a time lag of from 2 days to 3 days.

All the voids in the openwork gravel above the ground-water table show evidence of having been completely and firmly filled with clay. Downcutting by the river to bedrock has lowered the ground-water table far below its position when the gravel was deposited. All the clay in the voids of the openwork gravel exhibits shrinkage cracks in all excavations as the material is uncovered. The fact that Portland cement grout was injected into the material and, upon excavation, was seen to fill all cracks firmly and completely proves that the cracking of the clay is not induced by the admittance of air through the excavations. Below the ground-water table, and particularly within 5 ft of bedrock, there are voids which are only partly filled with clay, but certain clay void fillings exhibited shrinkage cracks identical in appearance to those above the water table.

The moisture content of the clay above the ground-water table is now between 65% and 118% of the dry weight. Although some swelling of the

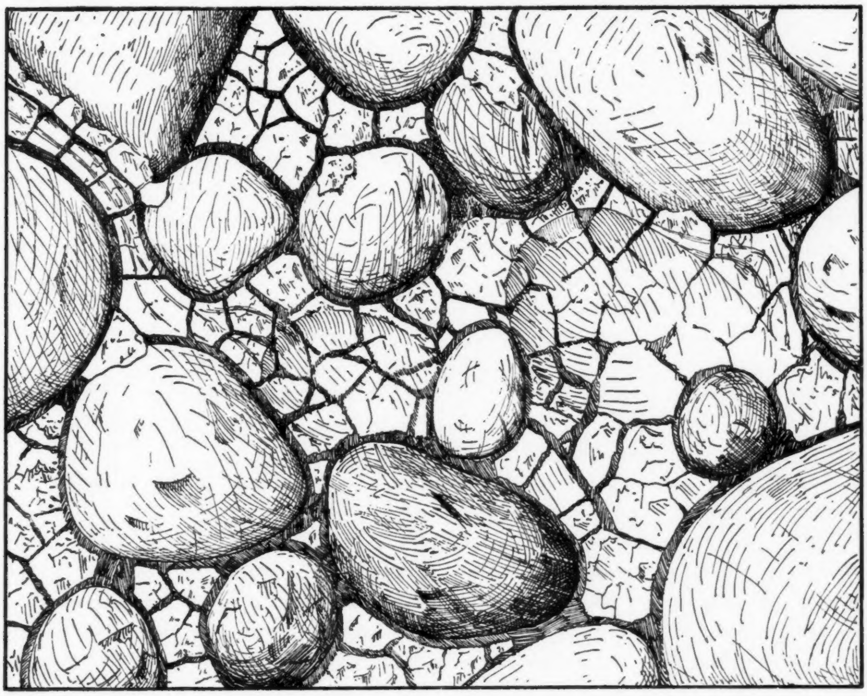

FIG. 6.—GENERAL DIAGRAM OF FLOW LINES

clay may take place when the completed dam submerges the gravel, it cannot be depended upon to swell enough to close the cracks completely. The fact that clay below the ground-water table exhibits cracks indicates that the clay-water mixture was not an equilibrium condition when the clay was deposited.

Resubmerging the clay above the present ground-water table cannot be expected to reduce the cracks to less than the openings below the water table.

The orgin of this clay filling again has no direct bearing on the origin of the gravel, but it does serve to emphasize the engineering significance. The clay could not have been deposited contemporaneously with the gravel since the openwork gravel requires very swift waters for its selective deposition and clay requires still water. It must then have been a secondary deposit in the voids. Two methods of introducing the clay suggest themselves: First, the clay may be introduced as a secondary deposit from nearly stagnant water in the gravel below river bed level. The mechanics in this case must necessarily have been a secondary wave of deposition following up from bedrock below the aggrading river that deposited the gravel. There is some question if the clay could have been deposited by this process in the dense state in which it is found. Allowing for swelling of the clay to fill the cracks and even allowing for some consolidation of the gravel mass by particle rearrangement when ice shove may have been active, the firmness of the clay seems incompatible with the depositional idea of origin.

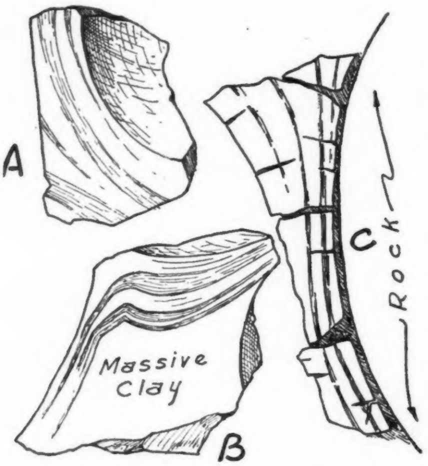

Fig. 7.—Flow Lines in Clay Blocks

A second method of introducing the clay requires a bed of clay and a bed of of gravel lying one above the other. Overriding ice, from 4,000 ft to 5,000 ft thick, could supply the pressure necessary to intrude the clay into all the voids in the gravel much as grout is intruded into aggregate to form "Prepakt" concrete. The presence of flow lines in individual blocks of clay, as shown in Figs. 6 and 7, suggests that it was intruded into the gravel. In Fig. 7, views A and B represent clay blocks sliced with a sharp knife and view C represents a clay block as it appeared upon exposure.

The presence of the clay introduces a lubricating element that could seriously affect the stability of the gravel under certain conditions. If ice shove has rearranged the pebbles in the deposit, then clay can be expected to be found between the pebble contacts. Running ground encountered in the tunnel suggests that there are zones in which the clay will act as a lubricant and this serves as a warning that seepage through the gravels may be a very dangerous thing.

Cedar River Failure in Washington.—The excessive leakage that led to the failure of the Cedar Reservoir on the Cedar River is attributed by J. Hoover Mackin[9] (1941) to "* * * the essential continuity of a sequence of open-

[9] "A Geologic Interpretation of the Failure of the Cedar Reservoir, Washington," by J. Hoover Mackin, *Bulletin No. 107*, Univ. of Washington Eng. Experiment Station, Seattle, Wash., 1941, p. 28.

textured (openwork) gravels from the pool to the steep north face of the embankment" where the failure occurred, at least 6,000 ft away. This failure emphasizes, as no other example possibly could, the significance of openwork gravel in engineering works.

Acknowledgment

The writer wishes to express his appreciation to Mr. Mackin, who, over a period of ten years, has listened patiently to innumerable discussions and read innumerable drafts of the manuscript. Thanks also are due J. S. Grygiel, Major, Corps of Engineers, and to Howard T. Harstad, civil engineer, for their criticism, which, it is hoped, will make the paper more understandable to an engineer. Discussion of the origin of the clay void filling at Chief Joseph dam site with Arthur Casagrande, M. ASCE, and with Edwin B. Burwell, geologist, Office of the Chief of Engineers, Department of the Army, has helped to clarify the mechanics of its deposition.